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Determinants of co-contraction during walking before and after arthroplasty for knee osteoarthritis

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ABSTRACT

Background: Knee osteoarthritis patients co-contract in knee-related muscle pairs during walking. The determinants of this co-contraction remain insufficiently clear.
Methods: A heterogeneous group of 14 patients was measured before and one year after knee arthroplasty, and compared to 12 healthy peers and 15 young subjects, measured once. Participants walked on a treadmill at several imposed speeds. Bilateral activity of six muscles was registered electromyographically, and co-contraction time was calculated as percentage of stride cycle time. Local dynamic stability and variability of sagittal plane knee movements were determined. The surgeon's assessment of alignment was used. Pre-operatively, multivariate regressions on co-contraction time were used to identify determinants of co-contraction. Post-operatively it was assessed if predictor variables had changed in the same direction as co-contraction time.
Findings: Patients co-contracted longer than controls, but post-operatively, differences with the healthy peers were no longer significant. Varus alignment predicted co-contraction time. No patient had post-operative varus alignment. The patients' unaffected legs were more unstable, and instability predicted co-contraction time in both legs. Post-operatively, stability normalised. Longer unaffected side co-contraction time was associated with reduced affected side kinematic variability. Post-operatively, kinematic variability had further decreased.
Interpretations: Varus alignment and instability are determinants of co-contraction. The benefits of co-contraction in varus alignment require further study. Co-contraction probably increases local dynamic stability, which does not necessarily decrease the risk of falling. Unaffected side co-contraction contributed to decreasing affected side variability, but other mechanisms than co-contraction may also have played a role in decreasing variability.

1. Introduction

Knee osteoarthritis is one of the most prevalent afflictions of the elderly, with patients reporting pain and functional limitations (Kauppila et al., 2009; Laxafoss et al., 2010). Objectively, there is a loss of articular cartilage, visible as a narrowing of the joint space, particularly at the medial side (Hunter et al., 2009), and often accompanied by varus alignment. Other structures are also involved, and clinical investigation often reveals laxity of the knee joint (Lewek et al., 2004) and/or quadriceps weakness (Hortobágyi et al., 2005). Patients with knee pain (Heiden et al., 2009), or effusion (Torry et al., 2000), may alter their muscle activity, as do patients who feel unstable during gait (Schmitt and Rudolph, 2008). Over the last decade, muscle activation patterns in gait have drawn considerable attention in the knee osteoarthritis literature. It was often reported that patients co-contract longer, co-contract more, or have higher muscle activity during walking than controls (e.g., Benedetti et al., 1999; Briem et al., 2007; Childs et al., 2004; Heiden et al., 2009; Hortobágyi et al., 2005; Hubley-Kozey et al., 2006; Lewek et al., 2003; Rudolph et al., 2001; Schmitt and Rudolph, 2007; Zeni et al., 2009).

Co-contraction may be beneficial, but can also increase joint loading (e.g., Lewek et al., 2004), possibly leading to further loss of cartilage

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(Childs et al. 2004). Hence, to optimise treatment, we need to know why patients co-contract, that is: What is the effective stimulus for, and what are the possible advantages of, co-contraction? The literature suggests that co-contraction may be related to mechanical factors, such as alignment, stability, and/or variability. Unfortunately, the literature is largely observational, with cross-sectional comparisons of patients and healthy peers. Still, three studies assessed patients after knee arthroplasty (Benedetti et al., 2003; Hubley-Kozey et al., 2010; Wilson et al., 1996), some studies followed patients before and after high tibial osteotomy (Briem et al., 2007; Kean et al., 2009; Ramsey et al., 2007a, 2007b), and a few studies used reversible experimental manipulations (Ramsey et al., 2007a; Schmitt and Rudolph, 2008).

In a study of alignment, valgus perturbations in healthy subjects were found to increase muscle activity on the medial side of the joint (Buchanan et al., 1996). In another experimental study (Ramsey et al., 2007a), patients with varus alignment had more co-contraction on the lateral side of the joint, which decreased when a neutral-position brace was applied, but when the brace was removed, co-contraction increased again. Varus alignment was also suggested to induce co-contraction in studies of high tibial osteotomy. Successful realignment decreased co-contraction of VM (vastus medialis) and GM (gastrocnemius medialis; Ramsey et al., 2007b), but unsuccessful realignment led to more post-operative co-contraction of VM and MH (medial hamstrings), and of VL (vastus lateralis) and GL (gastrocnemius lateralis; Briem et al., 2007). This literature suggests that varus alignment induces co-contraction in knee osteoarthritis. Still a relationship between varus alignment and co-contraction was not always found (e.g., Schmitt and Rudolph, 2008).

In the lumbar spine literature, co-contraction could be “explained entirely on the basis of the need for the neuromuscular system to provide […] mechanical stability […]” (Cholewicki et al., 1997, p.2207). Co-contraction can be an effective strategy to provide stability (Gardner-Morse and Stokes, 2001), but in knee pathology, this was not always found. In anterior cruciate ligament rupture, sagittal plane stability during gait may be recovered by an unusual contraction of a hamstring (Boerboom et al., 2001), but in subjects who remained unstable, more general co-contraction was found (Lewek et al., 2003; Rudolph et al., 2001). In knee osteoarthritis, subjects with serious self-reported instability had more VM–MH co-contraction before, during, and after a frontal plane perturbation of gait (Schmitt and Rudolph, 2008), which suggests that self-reported instability is a determinant of co-contraction. Still, subjective instability (Fitzgerald et al., 2004) may be confounded by fear (Van Galen and Van Huygevoort, 2000; Vlaeyen et al., 1995), and to the best of our knowledge, the relationship between objective stability (Bruijn et al., 2009a) and co-contraction during walking with knee osteoarthritis remains to be established.

In a study on manual tracking (Selen et al., 2006), increased precision demands were found to induce co-contraction, which decreases kinematic variability. In knee osteoarthritis, reduced variability of knee movements has been reported (Fallah-Yakhdani et al., 2010; Lewek et al., 2006). Reduced variability may be harmful to the joint (Lewek et al., 2006), but increased variability suggests a lack of control, and coincides with a higher risk of falling (e.g., Hausdorff, 2007; Leitner et al., 2007; Maki, 1997). Earlier, we hypothesised that subjects with knee osteoarthritis co-contract in order to reduce variability (Fallah-Yakhdani et al., 2010), which may enhance the control over knee motion (e.g., Benedetti et al., 2003; Kean et al., 2009; Schmitt and Rudolph, 2008; Van Dieën et al., 2003). Some authors see co-contraction as a strategy to compensate for quadriceps weakness (e.g., Hortobágyi et al., 2005). When taken literally, this is a paradox, but maybe the argument is that a weaker quadriceps muscle often coincides with problems of control (Rudolph et al., 2007), which would be visible as increased variability.

The present study focused on determinants of co-contraction during gait in knee osteoarthritis patients, waitlisted for arthroplasty. Alignment, local dynamic stability, and kinematic variability were the variables of interest. The surgeon's assessment of alignment was registered, and self-reported fear of movement/reinjury was included. Objective local dynamic stability and variability of sagittal knee movements were determined. We hypothesised that pre-operative patients would co-contract longer than controls, that co-contraction time would decrease after surgery, and that determinants of co-contraction would change post-operatively in the same direction as co-contraction time. More specifically, we hypothesised that varus alignment and instability would lead to co-contraction, and that co-contraction would reduce variability.

2. Methods

2.1. Participants

We were interested in relationships with major impact, and opted for an intensive study with a small number of subjects, different surgeons, and different techniques of arthroplasty. Pre-operatively, 16 knee osteoarthritis patients enrolled, one of whom was never operated, whereas another found the measurements too demanding, resulting in 14 patients who were also measured 1 year after arthroplasty. Exclusion criteria were: replacement of the other knee, revision, other conditions interfering with gait, or inability to adhere to the protocol. Patients were compared with 12 self-reportedly healthy peers, with similar age, gender, and BMI, and with 15 young subjects. Orthopaedic surgeons used the Knee Society (KS) rating scale (Insall et al., 1989), including alignment, which was registered as varus, valgus, or normal. All participants signed an informed consent, after the local Medical Ethical Committee had accepted the project.

2.2. Data acquisition

To assess fear of movement/reinjury, the TAMPA scale for kinesiophobia was used (Dutch version; Vlaeyen et al., 1995). For expected pain during the experiment, VAS forms (Visual Analogue Scales) were used, from 0 mm (“no pain at all”) to 100 mm (“maximal pain”).

Bilateral muscle activity of RF (rectus femoris), BF, VL, VM, GM, and TA (tibialis anterior) was recorded with surface electromyography (EMG), in accordance with SENIAM recommendations (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles; Hermens et al., 1999). Pairs of electrodes (H93SG, MedCat supplies, Erica, The Netherlands) were placed with 2-cm centre-to-centre distance, and a reference electrode over the tibia. Data were recorded at 1000 samples/s with a Porti EMG recorder (TMS-international, Enschede, The Netherlands; input impedance $>10^{12}$ Ω, CMRR $>$ 90 dB, 22 bits AD conversion after 20× amplification).

For movement registration, clusters of 3 markers (Infrared Light Emitting Diodes), fixed on light metal plates, were attached with neoprene bands to the thighs, shanks, and heels of each subject. An optoelectric system, OptoTrak™ (Northern Digital, Waterloo, Ontario, Canada), with two 3-camera arrays, was used to record movements at 50 samples/s. When the OptoTrak recording started, a trigger pulse was sent to the Porti for synchronisation.

Participants were invited to walk on a treadmill. Gait parameters are dependent on speed, and seven speeds were used, 0.6–5.4 km/h (increments 0.8 km/h), in increasing order. Initially, some practice time was offered to the subjects. Each speed was maintained during 4 min, with EMG and kinematics recorded in the last 2. Subjects were encouraged to take a break whenever they wanted, and were instructed to indicate if the speed was too high. If so, the belt was stopped, and the preceding speed was designated as “maximum”.

2.3. Calculations

All calculations were performed with MATLAB 7.0.4 (The MathWorks, Natick, MA, USA). Heel strike was inferred from the minimum vertical position of the average heel marker, and "stride" was defined from one heel strike to the next on the same side.

EMG signals were high-pass filtered at 20 Hz (second order Butterworth filter), bandpass filtered between 49 and 51 Hz (fourth order), full-wave rectified, and low-pass filtered at 20 Hz (second order). After time-normalisation to 0–100% of stride time, mean and maximum EMG activities were calculated. *K*-means cluster analysis of peak EMG amplitude was used to determine when each muscle was on or off (Den Otter et al., 2006), with number of clusters set to 5, and the cluster with the lowest activity defined as "off". Because level of co-contraction may be confounded by pathology or pain (Mizner et al., 2005), we decided to use co-contraction time (cf. Benedetti et al., 2003), calculated as the percentage of stride cycle time in which agonist and antagonist were simultaneously on, averaged over all strides. This was done separately in the patients' affected and the unaffected leg for the following muscle pairs: RF–BF, VL–BF, VM–BF, VM–GM, and TA–GM. To determine if co-contraction time was confounded by stance time, we calculated an asymmetry index, as the ratio of stance times. For the young and the healthy peers, the numerator and denominator were selected randomly (from left and right leg) per subject, while in the patients, we calculated affected divided by unaffected stance time.

The angular velocity of sagittal knee movements was used for objective local dynamic stability (Bruijn et al., 2009a,b; Fallah-Yakhdani et al., 2010). Per subject per speed condition, a 5-dimensional state space was constructed from the original kinematic signal during the first 30 strides, and four copies with time delays of 10, 20, 30, and 40 samples. The Euclidian distance between the trajectories originating from each data point and its nearest neighbour were followed over time, averaged per moment in time, and expressed as natural logarithms. The Lyapunov exponent λ_S (S for "short", i.e., from 0.0 to 0.5 strides), expressing the increase of Euclidian distance per stride, was calculated as the slope of the divergence curve. Positive values imply divergence, that is, instability, with higher positive values revealing more instability. Also for "variability", the angular velocity of sagittal knee movements over the first 30 strides per speed was used (Fallah-Yakhdani et al., 2010). Since buckling occurs mostly in the beginning of the stance phase (Hsu et al., 1985), we used the first 10% of the stride cycle. Between-stride standard-deviations were calculated and averaged over this period per subject per speed condition.

2.4. Statistics

Since not all speeds could be realised by all patients, we used General Estimating Equations (GEE; cf. Liang and Zeger, 1986; Zeger and Liang, 1986), which can deal with missing values. GEEs were used throughout the study, calculating regression on an independent variable, for "factors" (nominal or ordinal), "co-variates" (ratio), or their interactions. For variables with a potential effect of Side, we used separate analyses for the patients' affected and unaffected leg, whereas in the control groups, the average of both legs was used. For speed-dependent variables, we started with "full factorial" models. Non-significant high-level interactions were left out, unless a main effect would disappear. This was repeated through the lowest level of interaction.

GEE calculates *P*-values in an overall model ("model effects"), as well as the *P*-values of specific factor values ("parameter estimates"), the latter compared to a reference (the young for Group, pre-operative values for Time, and normal alignment for Alignment). We analysed the effects of Group and Speed (Table 2). If there was a significant effect of, or interaction with, Group, the calculation was repeated for the patients versus healthy peers only. For the patients, we then calculated the effects of Time and Speed (Table 3), and post-operative values were compared to the single measurements of the control groups. To determine which variables predicted muscle co-contraction time pre-operatively, the univariate effects of speed were calculated, then all bivariate effects (speed plus one potential predictor), and multivariate GEEs were performed with all variables that were significant in these univariate or bivariate analyses (Table 4). If only one bivariate model revealed significant regression, this would then constitute the "multivariate" model. In the text, only multivariate results are discussed. Statistical analysis was performed with SPSS 17.0, using $P<0.05$ as threshold for significance. In the tables, significant model *P*-values are given, plus the corresponding regression coefficients (*B*), for factors from the parameter estimates.

Table 1
Initial patient characteristics ($N=16$, group K), compared to the healthy peers (H) and young controls (Y).

Patient/Group	M/F[a]	Age (years)	BMI	Pain[b]	TSK[c]	KS-K[d]	KS-F[d]	MWS[e] (km/h)	Alignment[f]	Surgery[g]
01	F	74	37.9	67	57	54	35	2.2	VAR	T
02	M	58	33.7	60	54	30	20	1.4	VAL	T
03	F	76	31.3	68	32	55	25	4.6	NOR	T
04	M	57	33.2	25	50	72	50	5.4	NOR	U
05	F	63	27.1	51	49	70	40	4.6	NOR	U
06	F	57	22.1	78	56	44	40	4.6	NOR	U
07	M	54	30.2	67	43	55	60	5.4	VAR	T
08	F	78	29.0	84	26	55	60	1.4	NOR	T
09	F	48	34.1	32	46	65	25	3.8	NOR	T
10	F	57	30.0	77	43	40	50	1.4	NOR	T
11	F	56	24.1	34	38	55	40	5.4	NOR	T
12	F	80	24.3	17	39	76	55	1.4	VAL	T
13	M	50	28.0	24	42	45	10	2.2	NOR	T
14	F	54	31.5	83	30	36	30	3.8	NOR	T
15	F	76	29.6	55	49	50	50	1.4	VAL	–
16	M	59	29.1	46	42	72	5	5.4	VAR	–
Group values: ratio or mean (SD)										
K	5/11	62.3 (10.7)	29.7 (4.1)	54.3 (22.3)	43.5 (9.1)	54.6 (13.7)	37.2 (16.9)	3.4 (1.7)	3/3/10	11/3
H	5/7	62.0 (12.6)	29.4 (4.9)	7.5 (14.9)	26.8 (7.2)	94.9 (2.2)	88.3 (5.8)	5.3 (0.2)	0/3/9	–
Y	4/11	22.9 (3.9)	22.1 (1.5)	3.7 (4.3)	31.4 (7.3)	98.0 (3.2)	90.0 (–)	5.4 (–)	1/1/13	–

–: irrelevant.
[a] M (male)/F (female).
[b] Expected pain during the experiment, 100 mm VAS scale.
[c] TSK: Tampa Scale for Kinesiophobia (maximum 68).
[d] KS-K: Knee Society knee score (optimum 100), and KS-F: Function score (optimimum 90).
[e] MWS: Maximum Walking Speed.
[f] VAR (varus)/VAL (valgus)/NOR (normal).
[g] Total (T)/Unicompartmental (U) Knee Replacement.

Table 2
Significant regression coefficients (*B*) from GEEs on co-contraction time (% of the stride cycle), local dynamic stability (λS), and kinematic variability (SD in first 10% of the stride cycle), with Group as factor—healthy peers (H), pre-operative patients (K), both compared to young controls—and Speed (0.6–5.4 km/h, 7 levels) as covariate. Separate analyses were performed with patients' affected and unaffected leg. If a significant effect of, or interaction with Group was found, a *post-hoc* K vs. H comparison was performed. Note that GEEs calculate regression equations, and the first row reads as: co-contraction time (% of the stride cycle) of RF–BF in the analysis including the patients affected leg equals 39.70 + 11.24 (for the patients) − 4.11 × speed.

Analysis		Intercept		Group[a]		Speed		Interaction	
		Model *P*-value[b]	*B*	Model *P*-value[b]	*B*	Model *P*-value[b]	*B*	Model *P*-value[b]	*B*
Including the patients'affected leg									
Co-contraction time:									
RF–BF		0.00	39.70	0.00	K: 11.24	0.00	−4.11		
	K vs. H	0.00	43.06			0.00	−3.26		
VL–BF		0.00	43.30			0.00	−5.38	0.02	K: 3.10 H: 2.30
	K vs. H	0.00	43.40			0.00	−2.76		
VM–BF		0.00	46.50			0.00	−5.75	0.00	K: 3.25 H: 2.05
	K vs. H	0.00	44.73			0.00	−3.20		
VM–GM		0.00	43.31	0.00	K: 12.09 H: 9.77	0.00	−7.35		
	K vs. H	0.00	56.45			0.00	−8.51	0.02	K: 3.14
TA–GM		0.00	33.96			0.00	−5.75		
Local dynamic stability (/stride):									
		0.00	2.34			0.00	−0.18	0.01	H: 0.08
	K vs. H	0.00	2.19			0.00	−0.11		
Kinematic variability (°/s):									
		0.00	0.29	0.01	K: −0.10	0.00	0.03		
	K vs. H	0.00	0.32	0.03	K: −0.13	0.00	0.02		
Including the patients' unaffected leg									
Co-contraction time:									
RF–BF		0.00	43.25			0.00	−5.39	0.02	K: 2.78
	K vs. H	0.00	42.35			0.00	−3.01		
VL–BF		0.00	43.31			0.00	−5.39	0.00	K: 3.47 H: 2.30
	K vs. H	0.00	43.00	0.01	K: 9.79	0.00	−2.62		
VM–BF		0.00	46.51			0.00	−5.75	0.00	K: 3.37 H: 2.06
	K vs. H	0.00	44.61	0.02	K: 8.38	0.00	−3.16		
VM–GM		0.00	43.86	0.00	H: 12.60	0.00	−7.56	0.00	K: 3.16
	K vs. H	0.00	56.45			0.00	−8.51	0.00	K: 4.10
TA–GM		0.00	33.05			0.00	−5.42		
Local dynamic stability (/stride):									
		0.00	2.34			0.00	−0.18	0.02	H: 0.07
	K vs. H	0.00	2.17	0.03	K: 0.23	0.00	−0.12		
Kinematic variability (°/s):									
	0.00	0.30	0.04	K: −0.07	0.00	0.03			
K vs. H	0.00	0.31			0.00	0.03			

[a] The number of young controls was 15 for all speeds, there were 1 12 healthy peers for the first six speeds and 11 for the highest speed, and the number of patients was 15 for the first speed, 16 for the second, 11 the third, 9 the fourth and fifth, 7 the sixth, and 4 for the highest speed.
[b] *P*-value in the overall model, which is not necessarily the same as the *P*-value of any specific parameterization.

3. Results

Initial characteristics of patients and controls are given in Table 1. The patients and the healthy peers had similar age ($P = 0.88$) and BMI ($P = 0.85$). Pre-operatively, maximum walking speed of the patients was lower than that of both control groups (*t*-tests, *P*-values < 0.001). One year after the operation, patients' maximum walking speed had increased, from 3.4 to 4.1 km/h ($P < 0.001$), but remained below the control groups (*P*-values < 0.01). Pre-operative patients had more fear of movement/reinjury and expected more pain than both control groups (*P*-values < 0.001). Post-operatively, patients' fear had reduced, from 43.5 to 38.3 ($P = 0.02$), as had their expected pain, from 54.3 to 28.1 ($P = 0.01$), but values remained above the control groups (*P*-values < 0.01). Pre-operative KS scores were below those of the control groups (*P*-values < 0.001), and improved after the operation, the knee score from 54.6 to 74.3 ($P = 0.004$), and the function score from 37.2 to 61.4 ($P = 0.001$), both still below the control groups (*P*-values < 0.001). Pre-operative patients had more varus alignment than the control groups (Table 1), but post-operatively, no patient had varus alignment, 6 patients had valgus, and 8 normal alignment.

3.1. The effects of Group and of Time in speed-dependent variables

The effects of Group (knee osteoarthritis patients, healthy peers, and young controls) and Speed are given in Table 2, and the effects of Time (pre-operatively, and 1 year post-operatively) and Speed in the patient group in Table 3. In both tables, significant interactions with Speed are given. Because of the low number of patients who could walk at the higher speeds (cf. footnote 1 in Table 2), these interactions are difficult to interpret, and in the text, only main effects are mentioned.

No asymmetry of pre-operative stance times was found, which suggested that co-contraction time was not confounded by stance time. Co-contraction time was 6–46% of stride time in the young, 8–44% in the healthy peers, 20–53% in the patients' unaffected, and 9–51% in the

Table 3
Significant regression coefficients (B) from GEEs on co-contraction 1 time (% of the stride cycle), local dynamic stability (λS), and kinematic variability (SD in first 10% of the stride cycle) with Time (pre-operative patient values vs. 1 year post-operatively) as factor, and Speed (0.6–5.4 km/h. 7 levels) as covariate. Separate analyses were performed with the patients' affected and unaffected leg. There was one significant Time × Speed interaction, in the analysis of local dynamic stability that included the unaffected leg: $P = 0.049$, $B = 0.09$. Post-operatively, there were 14 patient data at the first and second speed, 11 at the third, 10 fourth, 9 fifth and sixth, and 7 at the highest speed.

	Intercept		Time		Speed	
	model *P*-value	*B*	model *P*-value	*B*[a]	model *P*-value	*B*
Including the patients' affected leg						
Co-contraction time:						
RF–BF	0.00	48.94	0.02	F: −3.47	0.00	−3.39
VL–BF	0.00	48.36	0.03	F: −5.07	0.00	−2.67
VM–BF	0.00	47.84	0.04	F: −3.99	0.00	−2.74
VM–GM	0.00	50.17			0.00	−4.63
TA–GM	0.00	39.33	0.01	F: −5.99	0.00	−5.90
Local dynamic stability (/stride):						
	0.00	2.11			0.00	−0.13
Kinematic variability (°/s):						
	0.00	0.24	0.02	F: −0.09	0.00	0.05
Including the patients' unaffected leg						
Co-contraction time:						
RF–BF	0.00	48.85			0.00	−3.35
VL–BF	0.00	52.31	0.03	F: −5.65	0.00	−2.77
VM–BF	0.00	51.70	0.03	F: −6.18	0.00	−2.83
VM–GM	0.00	49.79			0.00	−4.34
TA–GM	0.00	39.41			0.00	−4.77
Local dynamic stability (/stride):						
	0.00	2.41	0.01	F: −0.49	0.00	−0.18
Kinematic variability (°/s):						
	0.00	0.33	0.00	F: −0.18	0.00	0.02

[a] F: at follow-up after 1 year.

patients' affected leg. In all GEE analyses (Tables 2 and 3), co-contraction time decreased with increasing speed (P-values < 0.001). Pre-operative analysis (Table 2) revealed that in one muscle pair the patients, in another the healthy peers, and in still another both elderly groups co-contracted longer than the young. Moreover, co-contraction time was longer in the patients' unaffected VL–BF and VM–BF compared to the healthy peers (Fig. 1). Post-operatively, patients' co-contraction time had decreased in six muscle pairs (Table 3, cf. Fig. 2). Patients still co-contracted longer than the young in seven pairs (P-values < 0.05), but differences with the healthy peers were no longer significant.

Inspection of the graphs of sagittal plane knee movements revealed that 28 kinematic time series (of the 304, i.e., 9.2%, all from patients or healthy peers) were noisy or highly irregular. We removed these from the analysis of stability and variability. Group averages of λ_S ranged from 1.4/stride (least unstable) to 2.2/stride (most unstable). In all GEE analyses (Tables 2 and 3), the stability of sagittal plane knee movements increased with speed (P-values ≤ 0.02). Pre-operatively (Table 2), the patients' unaffected leg was less stable than the legs of the healthy peers. Post-operatively (Table 3), unaffected leg stability had increased, and was no longer different from the healthy peers.

Group averaged variability ranged from 0.21°/s to 0.44°/s. In all analyses, the variability of sagittal plane knee movements increased with speed (P-values ≤ 0.002). Pre-operatively (Table 2), the patients' affected and unaffected knee movements were less variable than those of the young, and knee movements in the patients' affected leg were less variable than in the healthy peers. Post-operatively (Table 3), variability of knee movements in both patients' legs had further decreased, and the differences with the control groups were even larger than before (P-values < 0.009).

3.2. Determinants of pre-operative co-contraction

The three patients with pre-operative valgus alignment did not walk faster than the second speed, and were removed from the analysis of predictors. Significant multivariate regressions per muscle pair are given in the columns of Table 4. Again, only main effects are mentioned in the text. Significant models were found for all ten muscle pairs analysed. In five models, higher speed predicted shorter co-contraction time. Varus alignment predicted longer co-contraction in four models. Affected side instability predicted affected side co-contraction time in four models, and unaffected side instability predicted unaffected side co-contraction in one. Finally, less variability at the affected side predicted longer co-contraction time at the unaffected side in three models.

4. Discussion

Preoperative patients had lower maximum walking speed than controls, had more fear of movement/reinjury, expected more pain, and had lower Knee Society knee and function scores. One year post-operatively, patients had improved in all these variables, but were still different from controls. Before the operation, three patients had varus alignment, after the operation none.

Patients co-contracted significantly longer than the young in two muscle pairs, and in two other muscle pairs when compared to the healthy peers. Post-operative co-contraction time tended to be shorter, and was no longer significantly different from the healthy peers. Sagittal knee movements of the patients' unaffected leg were less stable than of the healthy peers, but unaffected side stability had increased after the operation, and was no longer significantly different from the healthy peers. Patients' sagittal plane knee movements were less variable than in the controls, particularly at the affected side. Post-operatively, kinematic variability had further reduced (cf. Fallah-Yakhdani et al., 2010).

Pre-operative patients had longer co-contraction time in one or more muscle pairs when they had varus alignment, or when their sagittal plane knee movements were unstable. Moreover, negative regressions were found between affected side variability of sagittal plane knee movements and unaffected side co-contraction time.

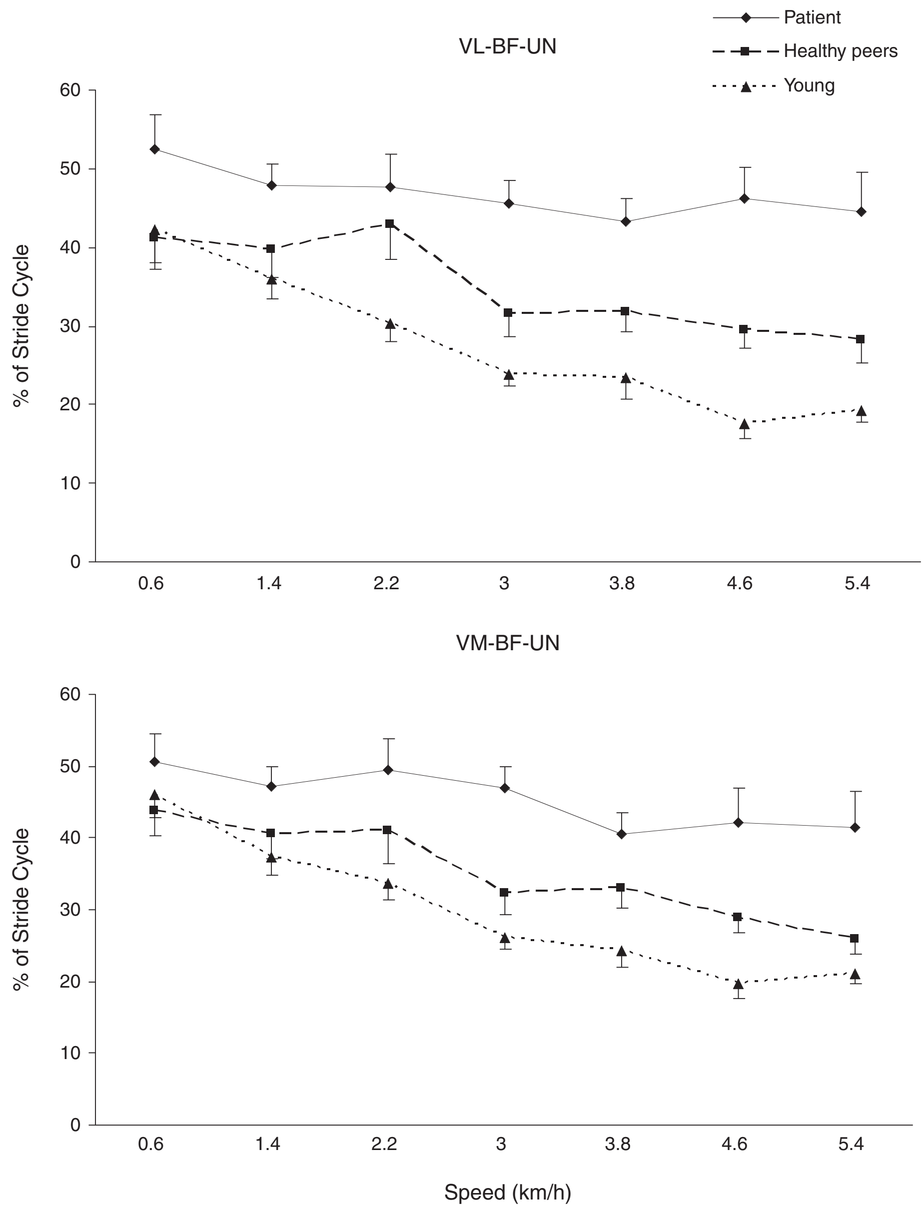

Fig. 1. Pre-operative between-group differences in co-contraction time (% of stride cycle) of the vastus lateralis and the biceps femoris (top), and of the vastus medialis and the biceps femoris (bottom), at the patients' unaffected side ("UN"), for 7 speed levels. Error bars represent standard errors.

4.1. Methodological considerations

Most studies use age-matched controls (e.g., Hortobágyi et al., 2005; Rudolph et al., 2007), but we also controlled for BMI, which may explain why the differences between patients and their healthy peers were relatively small (cf., e.g., Benedetti et al., 2003).

In the present study, co-contraction *time* decreased with increasing speed, while the *level* of co-contraction was reported to increase with speed (Zeni et al., 2009). These results are not necessarily in conflict, and together may imply that at higher speed co-contraction is shorter but more intense. Anyhow, co-contraction depends on walking speed. Most of the literature reports at self-selected speed, which will be slower for the patients, and could bias the results.

Different measures for co-contraction have been used: co-contraction time (e.g. Benedetti et al., 2003), ratios for the amount of co-contraction (e.g. Hortobágyi et al., 2005; Lewek et al., 2004; Rudolph et al., 2007), or scores based on pattern recognition in electromyograms (e.g. Hubley-Kozey et al., 2006). Interestingly, the differences between these measures did not affect the finding that patients co-contract more, or longer, than controls.

4.2. Co-contraction

Pre-operatively, co-contraction time was longer in the patients' unaffected VL–BF and VM–BF than in the healthy peers. Lewek et al. (2006) reported more VM–GM co-contraction in both patients' legs. Thus, unaffected leg co-contraction was reported before, but different muscle pairs were involved. Similar is true, at least in part, for affected legs. Rudolph et al. (2007) found more affected side VL–GL and VM–GM co-contraction in patients than in young controls, whereas in the present study, the patients had longer affected side RF–BF and VM–GM co-contraction than the young.

Hubley-Kozey et al. (2009) suggested that early stages of knee osteoarthritis lead to lateral co-contraction, compensating for medial problems, whereas later stages of osteoarthritis induce more "general co-activity" (p. 411; cf. also Heiden et al., 2009). The present study dealt

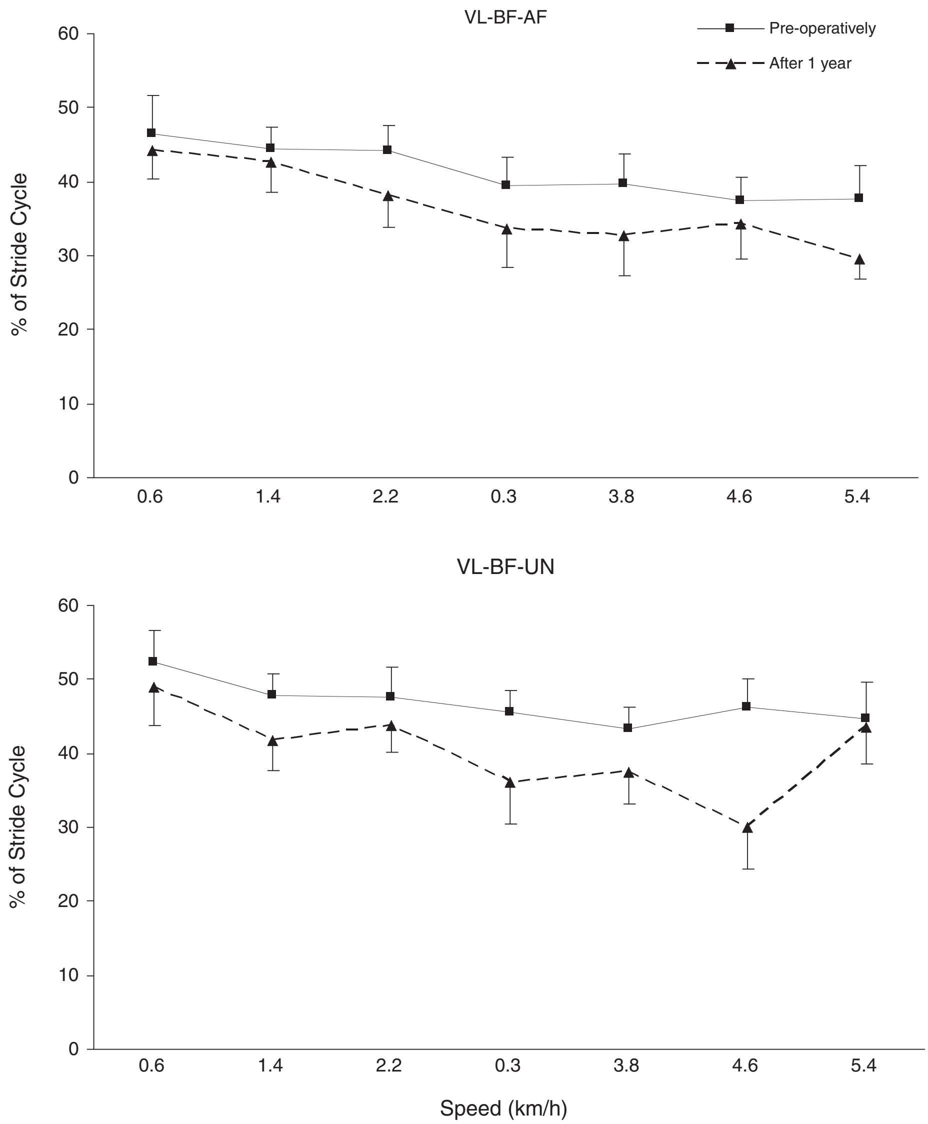

Fig. 2. Co-contraction time (% of stride cycle) of the vastus lateralis and the biceps femoris at the affected side (top, "AF"), and of the same muscles at the patients' unaffected side (bottom, "UN"), for 7 speed levels, pre-operatively versus 1 year after the operation. Error bars represent standard errors.

with patients before and after knee replacement. Co-contraction time decreased post-operatively in the majority of muscle pairs, which indirectly confirms Hubley-Kozey's idea of general "co-activity". In patients with severe medial knee osteoarthritis, Lewek et al. (2004) found medial co-contraction, which may increase loading of the medial side, and possibly reflects "an inability of the subjects […] to control knee instability by any other means" (p. 750). Alternatively, these results can be seen to confirm that patients with severe osteoarthritis use general co-contraction. In fact, it may be impossible to predict exactly in which muscle pairs patients will co-contract.

High tibial osteotomy was also reported to reduce co-contraction (Ramsey et al., 2007b), and in knee arthroplasty (Hubley-Kozey et al., 2010), lower muscle activity was reported after the operation. Thus, the fact that co-contraction time reduced post-operatively is in line with the literature.

4.3. Alignment

Pre-operatively, 3 patients were classified with varus alignment, but post-operatively, no varus alignment was found. Notwithstanding the fact that these numbers were small, varus alignment significantly predicted longer co-contraction time in several muscle pairs, which suggests that the effect of alignment on co-contraction is large. Moreover, alignment changed post-operatively in the same direction as co-contraction time. Thus, our results confirm (Briem et al., 2007; Ramsey et al., 2007a,b), but do not prove that malalignment is a determinant of co-contraction. Perhaps, patients with varus alignment rely more on the unaffected leg, and increase its stiffness by co-contracting. At the affected side, co-contraction may enhance frontal plane stability (Bennell et al. 2008), or reduce the knee adduction moment (Heiden et al., 2009; Ramsey et al., 2007a). Neither of these potential mediators was measured in the present study, and we conclude that patients with varus alignment co-contract longer, whereas the benefits of co-contraction with respect to alignment require further study.

4.4. Local dynamic stability

Pre-operative instability of sagittal knee movements predicted co-contraction time in several muscle pairs on the same side. Post-operatively, stability and co-contraction time were no longer different from the healthy peers. Regression does not prove causation,

Table 4
Significant multivariate regression (bold) of predictor variables on pre-operative muscle co-contraction time (% of the stride cycle), at the patients' affected and unaffected side, with Speed (0.6–5.4 km/h. 7 levels) as covariate. First, a univariate analyses were performed of the effects of Speed on co-contraction time. Then, all bivariate predictor × Speed analyses were performed. Significant regressions were entered into multivariate analysis. Significant univariate or bivariate regression that was not significant in the multivariate model is given in table, in normal rather than bold text. Note that each multivariate model should be read vertically. The first column, for instance, reads as: co-contraction time (% of the stride cycle) of RF–BF in the affected leg equals − 6.32 × speed (for subjects with varus alignment) + 23.74 × affected stability − 6.18 × speed × affected stability.

		Affected					Unaffected				
		RF–BF	VL–BF	VM–BF	VM–GM	TA–GM	RF–BF	VL–BF	VM–BF	VM–GM	TA–GM
Intercept[a]	*P*			**0.00**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	B			**19.25**		**36.93**	**38.82**	**52.35**	**56.44**	**55.82**	**59.54**
Speed	*P*	0.00	0.01	**0.00**	0.00	**0.00**	0.00	0.01	**0.01**	**0.00**	**0.00**
	B	− 3.14	− 2.28	**− 9.63**	− 5.39	**− 5.58**	− 2.62	− 1.93	**− 2.95**	**− 10.31**	**− 8.82**
Alignment	*P*					**0.04**	0.02	0.00	**0.01**	**0.00**	**0.00**
	B					**14.92**	10.20	9.47	**9.97**	**14.66**	**18.99**
Interaction	*P*	**0.00**	**0.00**	**0.00**							
	B	**− 6.32**	**− 4.48**	**− 5.69**							
Stability Af	*P*	**0.00**	**0.00**	**0.00**	**0.02**					0.02	0.03
	B	**23.74**	**28.94**	**16.07**	**16.31**					9.74	10.30
Interaction	*P*	**0.01**	**0.03**	0.00	**0.02**						
	B	**− 6.18**	**− 5.71**	− 7.92	**− 9.11**						
Stability Un	*P*						**0.00**		0.04		
	B						**8.03**		7.78		
Interaction	*P*						**0.02**				0.00
	B						**− 2.47**				− 7.29
Fear	*P*										
	B										
Interaction	*P*		**0.00**	**0.00**	0.047		**0.00**			0.00	
	B		**0.14**	**0.21**	0.24		**0.15**			0.17	
Expected pain	*P*							0.02			
	B							0.30			
Interaction	*P*							0.02			
	B							− 0.06			
Variability Af	*P*				0.02		**0.01**	**0.01**	**0.00**	0.01	
	B				− 22.24		**− 21.72**	**− 20.40**	**− 30.23**	− 27.85	
Interaction	*P*		0.01		0.02				**0.03**	**0.01**	
	B		10.63		9.07				**5.62**	**12.69**	
Variability Un	*P*	0.04	0.04	0.01							0.01
	B	12.33	11.72	15.65							26.37
Interaction	*P*										0.02
	B										− 14.66

[a] Significant intercepts are only given for the multivariate models.

but the experimental literature on spinal stability (Cholewicki et al., 1997; Van Dieën et al., 2003) revealed that instability may trigger co-contraction, and we conclude that this is also true for the osteoarthritic knee (cf. Buchanan et al., 1996).

Co-contraction would be expected to increase local stability. In the sagittal plane, co-contraction may reveal a "stiffening strategy" to prevent buckling (Childs et al., 2004; Lewek et al., 2006; Rudolph et al., 2007). Still, static and dynamic stability are very different concepts (Reeves et al., 2007), and increasing knee stability does not imply that the risk of falling is reduced. In fact, the opposite could be true.

Schmitt and Rudolph (2008) argued that "muscle cocontraction [...] appears to be an ineffective strategy to stabilise the knee" (p. 1180), but this may be a moot point, since it is likely that, without co-contraction, movements would be more unstable, and increasing co-contraction would, e.g., increase the load on the joint. Clearly, the control system must strike a balance between the advantages and disadvantages of co-contraction.

Table 4 shows that fear of movement/reinjury predicted less decrease of co-contraction time with speed in several multivariate models. Hence, fear of movement/reinjury may prevent patients to relax control when they walk faster. In knee osteoarthritis, self-reported instability was reported to predict co-contraction (Schmitt and Rudolph, 2008), but in knee osteoarthritis, it remains unclear how self-reported instability relates to objective instability, or if fear is part of the subjective experience of being unstable. All we can presently conclude is that knee osteoarthritis patients probably co-contract to stabilise the knee.

4.5. Variability of sagittal plane knee movements

The negative regression between affected side variability and unaffected side co-contraction time appears to confirm our hypothesis that co-contraction decreases variability (Fallah-Yakhdani et al., 2010). Leg kinematics just after heel strike are co-determined by the kinematics of the other leg, which may explain how *unaffected* side co-contraction can decrease *affected* side variability. Still, we do not know why this was the only significant regression between variability and co-contraction. Moreover, the present study does not exclude other mechanisms to decrease variability, such as paying more attention (cf. Fallah-Yakhdani et al., 2010).

Variability had further decreased after the operation, when patients' co-contraction time was no longer significantly different from the healthy peers. Perhaps, factors that increase variability, such as pain (Bandholm et al., 2008; Madeleine et al., 2008), had reduced, while patients continued to decrease variability through other mechanisms than co-contraction. We conclude that pre-operative unaffected side co-contraction contributed to reducing affected side variability, whereas the mechanisms relating co-contraction and variability require further study.

4.6. Limitations

Pre-operatively, one patient preferred to start at the second speed, which was the only speed realised at both measurement points by all patients. Only some patients could reach the highest speed, which made it difficult to interpret statistical interactions. We therefore largely refrained from interpreting interactions.

Treadmill and overground walking are known to be different (Dingwell et al., 2001). Moreover, heterogeneity reduces power, but many significant results were found, which suggested that results were major, Still, replication of the present study will be required before definitive conclusions can be reached.

Maximum Voluntary Isometric Contraction (MVIC) is affected by pathology (Mizner et al., 2005), and may bias patient EMGs. Hence, we calculated duration rather than amount of co-contraction. Although different co-contraction measures may have different advantages and disadvantages, the present findings are largely in line with studies that used other measures of co-contraction.

With surface markers in optoelectronic registration of knee movements, only flexion/extension can be reliably assessed (Leardini et al., 2005), and we refrained from estimating frontal plane stability. Nor did we measure the knee adduction moment. These decisions limited our potential to understand the benefits of co-contraction in varus alignment.

4.8. Conclusion

Pre-operatively, patients co-contracted longer than young controls in two, and longer than their healthy peers in two other muscle pairs. Post-operatively, co-contraction times were no longer different from those in the healthy peers. Pre-operatively, varus alignment induced longer co-contraction. The benefits of co-contraction with respect to alignment deserve further study. Sagittal plane instability triggered longer co-contraction, which probably increased the stability of the knee. Nevertheless, increased knee stability does not imply that subjects will fall less. Unaffected side co-contraction contributed to decreasing affected side sagittal plane variability. Post-operatively, however, variability had continued to decrease, which requires further study. The hypothesis that predictor variables would change post-operatively in the same direction as co-contraction time, was confirmed for alignment and unaffected side instability, but falsified for variability.

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